MEASUREMENTS OF ULTRAHEAVY COSMIC RAYS WITH HEAO-3

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the 60th birthday of Frank B. McDonald

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Abstract

The HEAO-3 Heavy Nuclei Experiment has measured abundances of elements from ${}_{18}$Ar to ${}_{92}$U in the cosmic rays. The results on the ultraheavy elements, those with atomic number greater than 30, indicate that the sources of cosmic rays contain a mixture of r-process and s-process material similar to that found in the solar system. This result is at variance with previous indications that the sources are greatly enhanced with freshly synthesized r-process material. Apparent discrepancies between our results and the accepted solar-system abundances have led to a re-examination of data on photospheric abundances of Ge and Pb, resulting in suggested reductions in their values.

Introduction

It is appropriate to discuss the ultraheavy (UH) cosmic rays (nuclei with atomic number, Z, greater than 30) in a volume which honors the career of Frank McDonald. While Frank has not participated directly in experiments to measure these very rare nuclei, he has had a major influence on work in this field, both by his pioneering research in the mid-1950's with multiparameter counter techniques for identifying cosmic-ray elements, and by his leadership in the late 1960's and the 1970's in establishing and guiding the High Energy Astronomy Observatory (HEAO) program. The best data to date on the elemental composition of UH cosmic rays has come from the Heavy

Nuclei Experiment which flew on HEAO-3, and this instrument used a multiparameter counter technique which is a direct descendent of that used in Frank's early work.

The first counter telescope which used the dE/dx-Cherenkov technique was flown by Frank on balloons in 1955 (McDonald 1956). In those flights he used a NaI scintillation counter and a Lucite Cherenkov counter to measure the cosmic-ray alpha-particle energy spectrum. Subsequently Frank and Bill Webber extended the use of this technique in an important series of balloon flights which measured the proton and alpha-particle energy spectra and their variation over several years (McDonald and Webber 1959; McDonald 1959; McDonald and Webber 1960).

In the late 1960's Frank was the principal motivator behind plans for a "Super Explorer" program in which a new class of very large instruments for high energy astrophysics could be placed in orbit. His efforts led in 1970 to a solicitation for proposals for experiments to be flown on a series of High Energy Astronomy Observatories. In 1971, a number of x-ray, gamma-ray, and cosmic-ray experiments were selected for two large HEAO spacecraft. Our Heavy Nuclei Experiment was among those selected for the first HEAO, which at that time was scheduled for launch in 1975. In early 1973, impelled by budget problems in NASA, the HEAO program was reconfigured to three smaller spacecraft; and our experiment was moved to the third of these, scheduled for launch in 1979. As HEAO project scientist, Frank played a major role in maintaining the scientific viability of the HEAO program in the face of these difficult redesigns.

HEAO-3 was launched on September 20, 1979, into a circular orbit with initial altitude 496 km and inclination 43.6 degrees. The spacecraft returned data until the end of May, 1981. The Heavy Nuclei Experiment (Binns *et al.* 1981) was composed of six dual-gap parallel-plate pulse ionization chambers, a Cherenkov counter with Pilot-425 (Plexiglass doped with wavelength shifter) radiators, and four layers of dual-coordinate multiwire ionization hodoscopes. The instrument used the dE/dx-Cherenkov technique for measuring the nuclear charge of individual elements. The total geometry factor of the

HEAO Heavy Nuclei Experiment was approximately 5 m^2sr, although the best charge resolution was achieved by limiting analysis to particles that penetrated all the counters -- a geometry factor of approximately 1 m^2sr. This instrument achieved individual-element resolution for even-Z elements from $_{26}Fe$ through $_{58}Ce$, and achieved adequate resolution at higher atomic numbers to determine the ratio of the Pb-group to the Pt-group of elements and the relative abundance of actinide elements.

Preliminary results from this experiment were reviewed at the International Cosmic Ray Conference in Paris (Israel 1981) and in the proceedings of the 1982 summer course in Erice (Israel 1983a) where we also presented a summary of UH detector techniques (Israel 1983b). A later review appeared in a 1984 COSPAR symposium (Binns *et al.* 1984), and a more exhaustive review of UH cosmic rays is in preparation.

In this paper we summarize our results thus far which have a bearing on the elemental composition at the cosmic-ray source. The objective is to compare the observed cosmic-ray abundances with those expected from various plausible compositions at the cosmic-ray source, and from the comparison to study the nucleosynthesis history of these cosmic rays as well as elemental fractionation effects which may occur in the acceleration process. In so doing we concentrate on those elements whose observed abundances at earth are unlikely to include a very large component of fragments from the collisions of heavier cosmic rays with nuclei of the interstellar gas. For these elements, calculations which account for the interstellar fragmentation do not depend very sensitively upon the details of the model of galactic confinement of these nuclei, although some propagation calculations are essential to this analysis (Brewster *et al.* 1983, 1985; Margolis and Blake 1983, 1985).

Work on other aspects of this Heavy Nuclei Experiment is in progress, and preliminary results have been reported elsewhere. The abundances of secondary UH elements were discussed by Klarmann, *et al.* (1985). We have reported results from calibration of the instrument with relativistic heavy ions from the Bevalac at the Lawrence Berkeley

Laboratory (Newport *et al.* 1985) and preliminary results from studies of heavy ion fragmentation carried out in connection with this Bevalac calibration (Kertzman *et al.* 1985). This experiment has also allowed us to measure the relative abundances of Fe and Fe-secondary elements at energies up to several hundred GeV/amu (Jones *et al.* 1985]).

There are four groups of mainly-primary UH elements -- $32 \leq Z \leq 42$, $50 \leq Z \leq 58$, $76 \leq Z \leq 82$, and $Z \geq 90$. In the following section of this paper we summarize our results on each of these groups in turn.

Results

Prior to the results of this experiment, observations using passive detectors (nuclear emulsions and plastic track detectors) had indicated that the cosmic rays were greatly enriched in elements produced by r-process nucleosynthesis. The very large values found for the ratio of actinide elements ($Z > 89$) to elements of the platinum-lead group ($74 \leq Z < 84$), 10% or more, compared with the 1% expected from a cosmic-ray source with solar-system abundances, implied that the cosmic rays were significantly enriched in freshly synthesized r-process elements (Fowler *et al.* 1977; Shirk and Price 1978). Such enrichment would be expected if supernovae supply the energy for the cosmic rays and accelerate material from regions where r-process nucleosynthesis is taking place.

One of the principal achievements of this experiment has been the demonstration that this view was incorrect. We have found element abundances which are remarkably similar to those expected from a source with composition very similar to that of the solar system, when effects of fractionation dependent upon first-ionization potential are taken into account. Indeed the similarity is so striking that when our results for two elements (Ge and Pb) failed to fit with accepted solar-system abundances, investigators were stimulated to re-examine those abundances, concluding that photospheric abundances of those two elements are actually about a factor of two lower than the previously accepted values (Grevesse and Meyer 1985).

Our observed abundances of elements from $_{32}Ge$ through $_{42}Mo$ relative to Fe are displayed as data points in Figure 1 (Binns *et al.* 1984). The histograms in this figure compare the data with that expected from various source abundances. In each panel the solid-line histogram assumes no elemental fractionation at the source, while the dashed-line histogram assumes fractionation which depends exponentially on the element's first ionization potential (FIP). There is reasonably good agreement between the data and the prediction from solar-system abundances (Cameron 1982a) with FIP fractionation. Since the solar-system abundances for these elements are dominated by s-process nucleosynthesis (Cameron 1982b), there is also reasonable agreement between the data and the s-process prediction. The abundances of these elements relative to Fe are much greater than those of the r-process component of the solar system, and even if one renormalizes the r-process abundances, the pattern of element-to-element abundance variations does not match the data as well as a simple solar-system source.

One notable exception to the agreement between our data and the solar-system abundances is the element Ge. This element is well-resolved in our data, and its abundance relative to Fe is about half that which would be expected from the solar-system source. A similar conclusion is reached by examining the data from the other HEAO-3 cosmic-ray experiment, although that experiment has a smaller geometry factor and thus its conclusion about Ge abundance has lower statistical significance (Byrnak *et al.* 1983). This conclusion is the same whether one compares the cosmic-ray data with the Cameron (1982a) solar-system abundances or those of Anders and Ebihara (1982); and it is unaffected by any model of source fractionation in which first-ionization potential is the organizing parameter, because Fe and Ge have almost exactly the same value of FIP. We have previously noted (Israel *et al.* 1983) that the low observed Ge abundance could be explained if volatility were a significant factor in source fractionation, as had been suggested by several authors (Cesarsky and Bibring 1980; Epstein 1980; Bibring and Cesarsky 1981; Tarafdar and Apparao 1981; Meyer 1981). We also noted (Binns *et al.*

1984) that the low Ge abundance could indicate that there may be a difference between the C1-meteorite abundance of this element and the correct solar-system abundance.

In the face of this discrepancy between our Ge data and the standard solar-system abundances Grevesse and Meyer (1985) re-examined the spectroscopic data on the photospheric abundance of Ge. They concluded that the best estimate of the photospheric Ge abundance is lower that the C1 meteorite value (and the previously accepted photospheric value) by nearly a factor of two. When they use this new estimate of the photospheric abundance of Ge as the solar-system value, the discrepancy between cosmic-ray and solar-system Ge abundances disappears.

For the elements $_{50}$Sn through $_{58}$Ce, Figure 2 (Stone *et al.* 1983) compares measured abundances (data points) with abundances expected (histograms) from various sources. In this charge interval the solar-system abundances have about equal overall contributions from r-process and s-process nucleosynthesis, with the r-process dominating the production of $_{52}$Te and $_{54}$Xe and the s-process dominating $_{50}$Sn, $_{56}$Ba, and $_{58}$Ce. If one ignores the possibility of source fractionation dependent on the first-ionization potential, then the observed peaks of Sn and Ba suggest a distinct enhancement of s-process material. But these two s-process elements also have lower FIP than the Te and Xe, and thus FIP fractionation would be expected to increase the abundance of Sn and Ba relative to Te and Xe. When FIP fractionation similar to that found for lower-Z elements is applied to the possible sources, the data are found to be in reasonable agreement with a source abundance containing a mixture of r-process and s-process contributions in about the same proportions as is found in the solar system.

In the "platinum-lead" region the solar system abundances are dominated by an r-process peak of the elements $_{76}$Os, $_{77}$Ir, and $_{78}$Pt, and an s-process peak at the element $_{82}$Pb. In our experiment we were unable to resolve individual-element peaks at these high charges, but we did form a "Pb/Pt" ratio of charge groups with the "Pb" group including events with charge $81 \leq Z \leq 86$, and the "Pt" group including events with charge $74 \leq Z \leq 80$. We find a value of 0.25 ± 0.09 for this ratio (Binns *et al.* 1985). Figure 3 compares this result with that expected from a source with standard solar system abundances (Anders and Ebihara 1982) and with an r-process source derived from those solar system abundances (Fixsen 1985; Binns *et al.* 1985). Our observed "Pb/Pt" ratio is distinctly lower than that expected from this assumed solar-system source, suggesting an enhancement in r-process contribution to the cosmic-ray source. The UH experiment on the Ariel-6 spacecraft (Fowler *et al.* 1985) found a "Pb/Pt" ratio, 0.35 ± 0.12, which is consistent with our result.

As with the low observed Ge abundance, the low Pb abundance would be consistent with a volatility dependence of the source fractionation, without invoking a non-solar-system source abundance. However, here too Grevesse and Meyer (1985) were stimulated by our cosmic-ray measurement to re-examine the spectroscopic data on the photospheric abundance of Pb. They conclude that the best photospheric abundance for Pb is about 0.63 of the standard (C1 meteorite) abundance. If the "expected" solar system values in Figure 3 are multiplied by 0.63, then our observed value of this ratio is no longer significantly lower than that expected from a solar-system source. Thus the observed Pb/Pt ratio would not require a significant enhancement of r-process material.

Finally, we turn to the results on the heaviest elements, the actinides, $Z \geq 90$, summarized in Figure 4. Prior to our HEAO-3 and the Ariel-6 experiments, measurements with nuclear emulsions and plastic track detectors had indicated that in the cosmic rays the ratio of actinides to elements in the "Pt-Pb" region was at least an order of magnitude higher than in the solar system (Fowler *et al.* 1977; Shirk and Price 1978). Since the actinides are produced only by r-process nucleosynthesis, this actinide enrichment would have implied a very significant enrichment of freshly synthesized r-process material in the cosmic ray source.

The actinide abundances reported by Fowler *et al.* and by Shirk and Price were questioned by Meyer (1979) who concluded from an examination of their data that the evidence for such high abundances was not convincing. Resolution of these conflicting interpretations of the data did not come until the HEAO-3 and Ariel-6 data had been analyzed and O'Sullivan (1985) had re-evaluated the earlier balloon data. He concluded, in the light of new understanding of the temperature dependence of track registration in plastics, that the plastic-track balloon data were consistent with an actinide abundance substantially lower than that previously derived from those data.

By carefully examining all the high-charge events in our HEAO-3 data for which a reasonably accurate charge could be assigned, we found just one event which might well be an actinide (Binns *et al.* 1982). The assigned charge for this event was 89, but the very short half-lives of all the elements in the interval $84 \leq Z \leq 89$, combined with the poor resolution of this data set, makes it more probable that this was a nucleus of $_{90}$Th or $_{92}$U. At the same time, we cannot be certain that this single event was not in fact a $_{82}$Pb nucleus whose charge was significantly overestimated. Together with this event we found 101 events with $74 \leq Z \leq 87$, giving us an actinide to "Pt-Pb" ratio of about 1%, with an 84% confidence upper limit of 3%. The Ariel-6 result for the same ratio, based on three "actinide candidates" and 65 in the "Pt-Pb" group (Fowler *et al.* 1985) is 4.6% (+4.5%/-2.5%). With the very low actinide statistics in these experiments, both the HEAO-3 and the Ariel-6 results are consistent with a result formed by combining the two, 2.4% (+1.9%/-1.2%).

Since a cosmic-ray source with solar-system abundances gives about 1% for the expected value of this ratio, the observations are not inconsistent with such a solar-system source. Although with the very low observed statistics one cannot rule out a significant enhancement of r-process actinides in the cosmic-ray source, we can exclude the possibility that the cosmic rays consist primarily of freshly synthesized r-process material.

Discussion

The relative abundances of UH elements at the cosmic-ray source appear to be consistent with those expected from source abundances with a mix of r-process and s-process nucleosynthesis similar to the solar-system mix, provided one takes into account elemental fractionation dependent upon first-ionization potential, similar to the fractionation which has been observed for elements with atomic numbers below 30. However, it is important to recognize that limitations on statistics, particularly at the highest atomic numbers mean that we cannot exclude the possibility of factor-of-two differences between the r-process/s-process ratio in the solar system and that in the cosmic-ray source. Indeed, when we consider the differences between the isotopic composition of Ne, Mg, and Si at the cosmic-ray source and in the solar system (Wiedenbeck 1984) it would be surprising if the UH cosmic-ray source composition did not have some differences of perhaps as much as a factor of two from the solar system.

It had appeared that the cosmic-ray abundances of Ge and Pb were low by a factor of about two relative to nearby elements when our measurements were compared with abundances expected from the standard compilations of solar-system abundances based on C1 meteorites. But this discrepancy disappeared when data on photospheric abundances were re-examined and the new photospheric values were substituted for the C1-meteorite values in the compilation of solar-system abundances.

The picture that emerges from these new observations of UH cosmic rays is consistent with models of shock acceleration of cosmic rays in the interstellar medium. In these models, the energy of the cosmic rays comes from supernova explosions, but the nuclei themselves come from the interstellar medium. Since the solar system condensed out of interstellar medium, in these models one expects the cosmic-ray and solar-system abundances to be similar, although one might expect differences in detail owing to the differences in time and place at which these two sets of abundances sample the interstellar medium. Those detailed differences could be of great importance to our understanding of the chemical evolution of the galaxy, but their study awaits future experiments

(Drach *et al.* 1985) with individual-element resolution and much larger collecting power.

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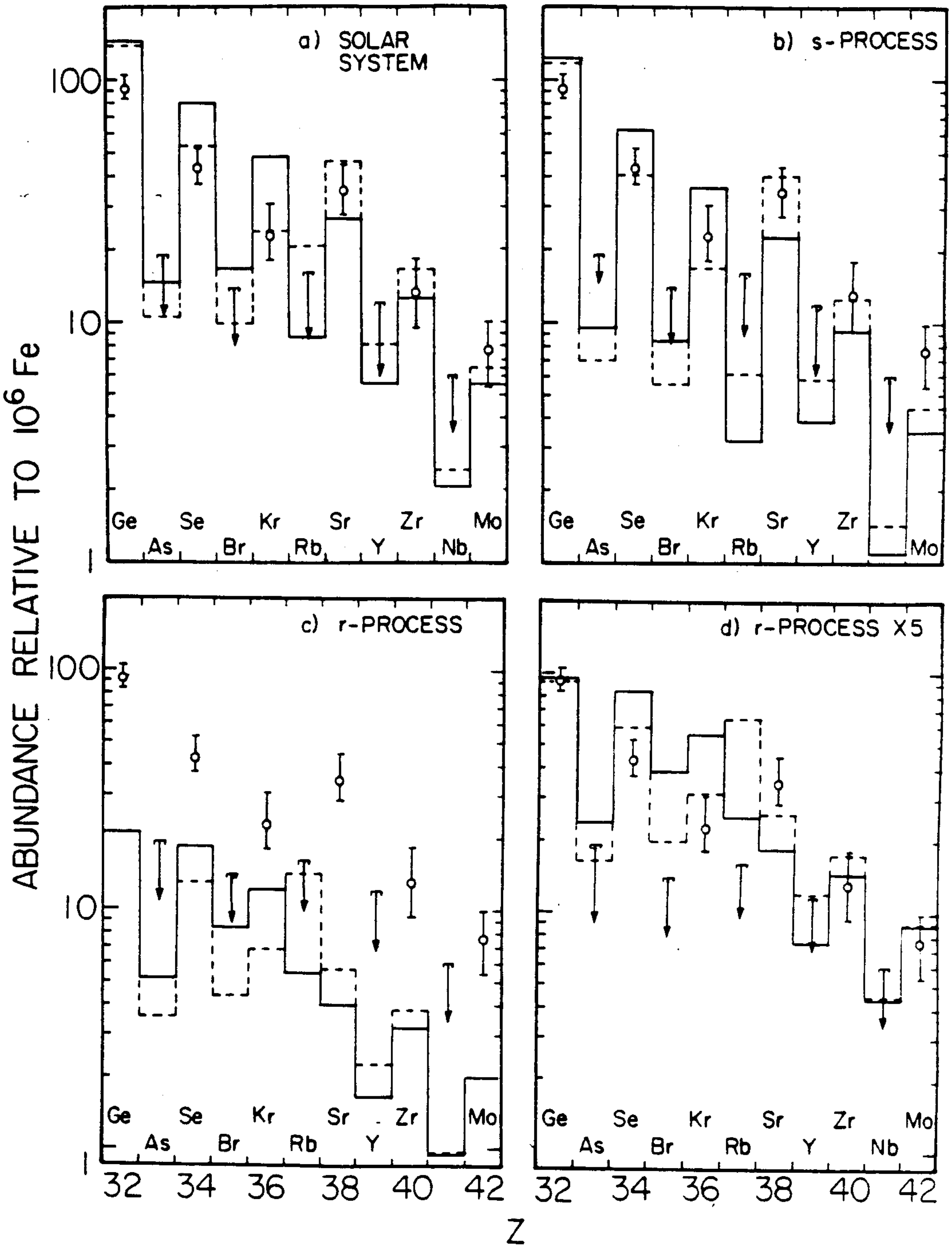
Figure Captions

1. Comparison of our measured abundances (data points) (Binns *et al.* 1983) with those expected at earth after galactic propagation, through an exponential path length distribution with mean 5.5 g/cm^2 of hydrogen, from a source with (a) solar system abundances (Cameron 1982a), (b) solar system s-process abundances (Cameron 1982b), (c) solar system r-process abundances (Cameron 1982b), and (d) solar system r-process abundances enhanced by a factor of 5. In each panel the solid line assumes no FIP fractionation and the dashed line assumes FIP fractionation of the form 9.31exp(-0.288FIP).

2. Comparison of our measured abundances (data points) with those expected at earth after galactic propagation, through an exponential path length distribution with mean 5.5 g/cm^2 from sources with solar system abundances (Anders and Ebihara 1982), s-process abundances (Käppeler *et al.* 1982), or r-process abundances (Krombel 1983). The upper panels assume no FIP fractionation and the lower panels assume exponential FIP fractionation of the form 9.31exp(-0.288FIP).

3. The ratio of "Pb" ($81 \leq Z \leq 86$) to "Pt" ($74 \leq Z \leq 80$). The data points are observations from HEAO-3 (Binns *et al.* 1985) and Ariel-6 (Fowler *et al.* 1985). The lines are expected values after propagation through an exponential path length distribution with mean 5.5 g/cm^2 from sources with standard solar system abundances (Anders and Ebihara 1982) or r-process abundances derived from those solar system abundances (Fixsen 1985; Binns *et al.* 1985). Solid lines assume no FIP fractionation, which for these elements is equivalent to a step-function FIP fractionation with step above 9 eV; dashed lines assume exponential FIP fractionation. Reduction of the solar-system Pb abundance as suggested by Grevesse and Meyer (1985) would lower the expected solar system values by a factor 0.63, as indicated by the dotted line, and would cause an even greater reduction in the r-process expectations.

4. The abundances of "actinides" ($88 \leq Z \leq 100$) relative to "Pt-Pb" ($74 \leq Z \leq 87$). Data are from balloons (Fowler *et al.* 1977), Skylab (Shirk and Price 1978), Ariel-6 (Fowler *et al.* 1985), and HEAO-3 (Binns *et al.* 1985). The revised balloon point is from O'Sullivan (1985). Expected values (Blake *et al.* 1978) are solid lines without FIP fractionation and dashed lines with FIP fractionation, for sources with composition of the solar system at the time of its formation or for a source with the composition of freshly synthesized r-process material. The dot-dash solar system line substitutes present-day abundances for the (solid line) abundances at the formation of the solar system.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b) s-PROCESS
c) r-PROCESS
d) r-PROCESS X5
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40
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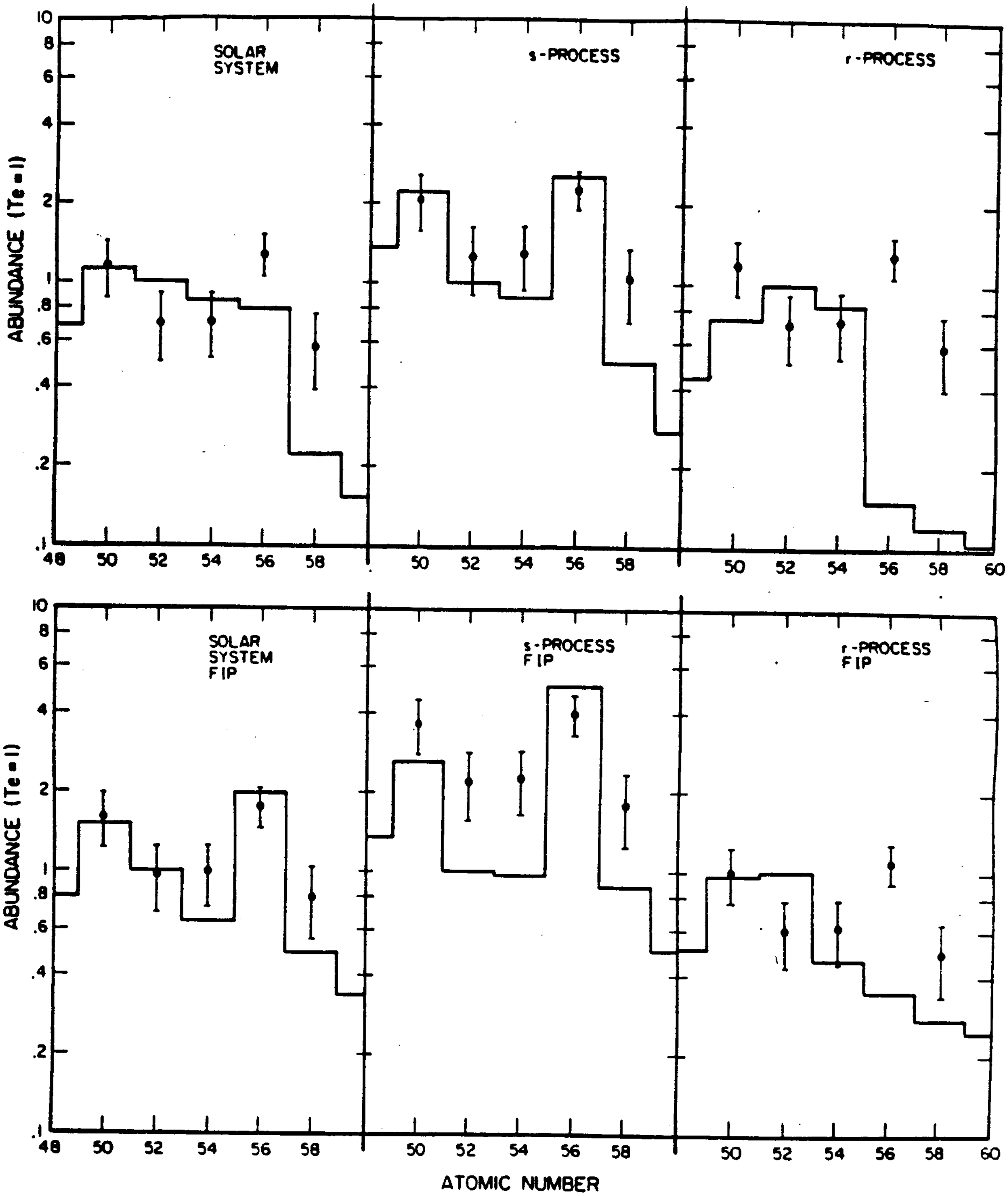
Z

Figure 1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s-PROCESS
r-PROCESS
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s-PROCESS FIP
r-PROCESS FIP
ABUNDANCE (Te = 1)
ATOMIC NUMBER
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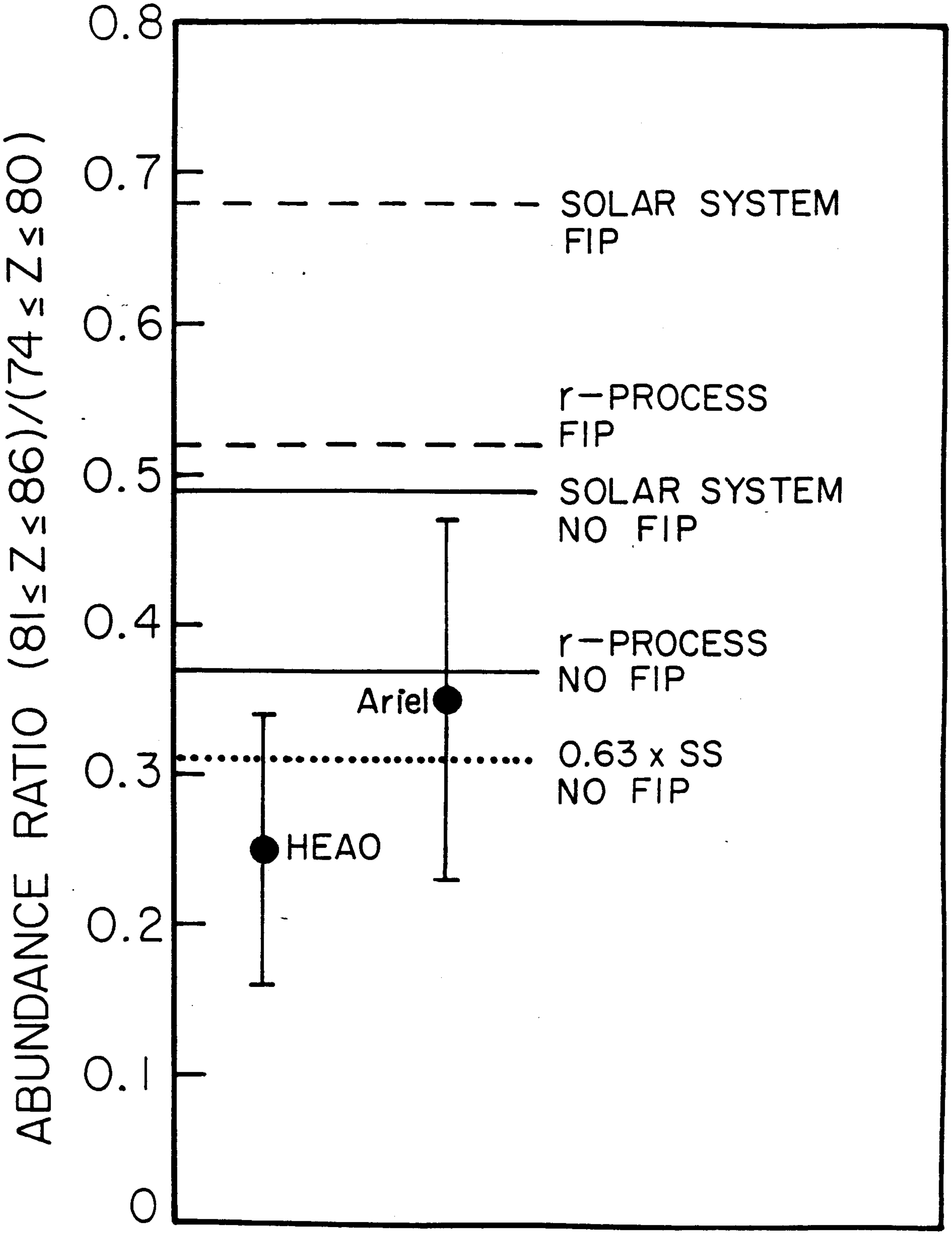
Figure 2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ABUNDANCE RATIO (81 ≤ Z ≤ 86)/(74 ≤ Z ≤ 80)
SOLAR SYSTEM
FIP
r−PROCESS
FIP
SOLAR SYSTEM
NO FIP
r−PROCESS
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0.63 x SS
NO FIP
HEAO

Figure 3

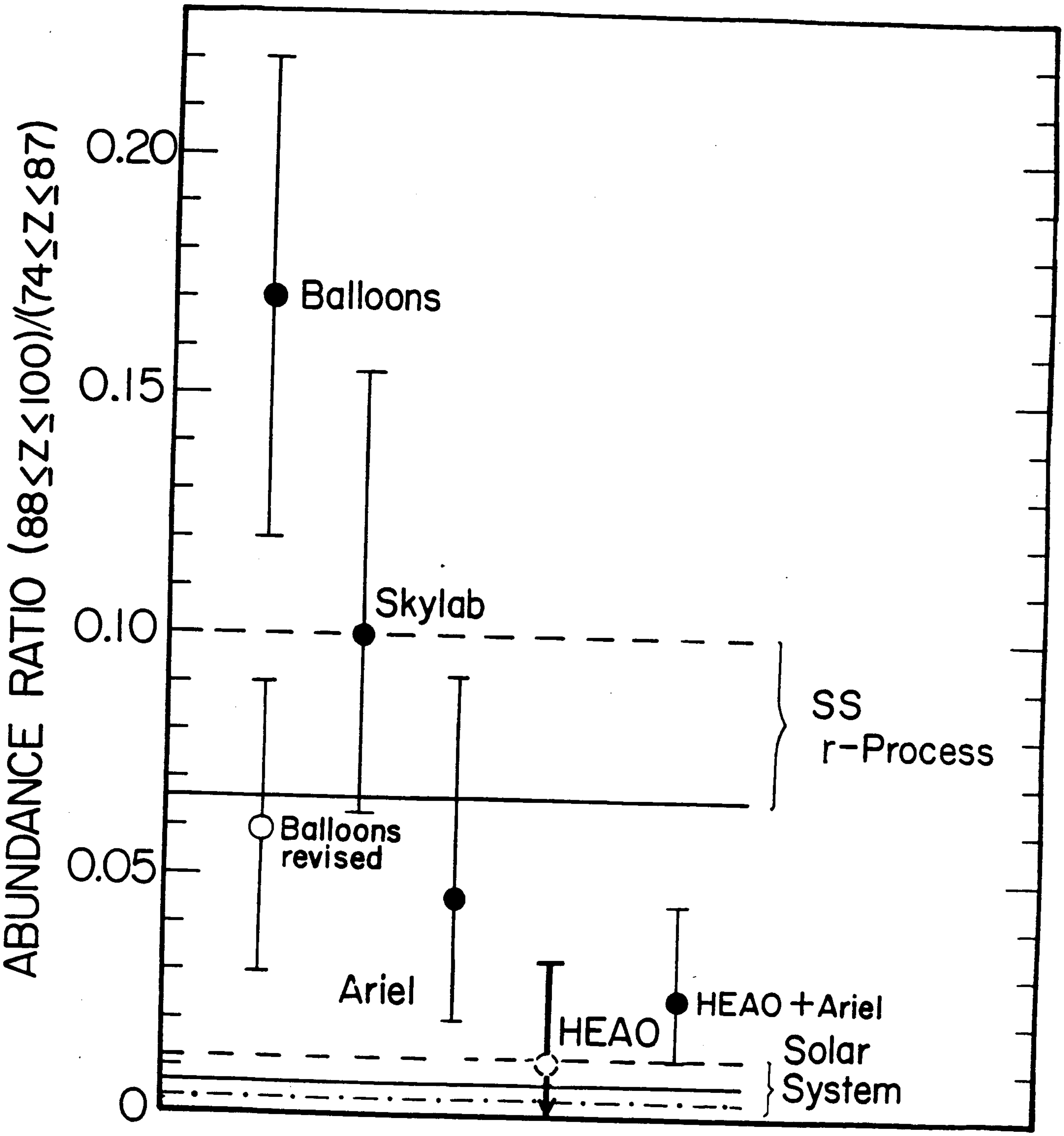
ABUNDANCE RATIO (88≤Z≤100)/(74≤Z≤87)
0.20
0.15
0.10
0.05
0
Balloons
Skylab
SS
r-Process
Balloons
revised
Ariel
HEAO
HEAO + Ariel
Solar
System

Figure 4